FINAL REPORT

Contract DAAK70-83-K-0018
(DARPA Order 3206)

"Autonomous Vehicle Navigation"

Submitted to: U.S. Army Night Vision and
Electro-Optics Laboratory
Fort Belvoir, VA 22060

COTR: Dr. George Jones

Submitted by: Computer Vision Laboratory
Center for Automation Research
University of Maryland
College Park, MD 20742

Principal Investigators: Azriel Rosenfeld
Research Professor

Lary S. Davis
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The research conducted on the contract was concerned with image understanding techniques applicable to autonomous vehicle navigation. Thirty-six technical reports were issued on the project. Abstracts of these reports are given on the following pages: numbers in brackets in the list below refer to these abstracts.

1) Time-varying image analysis and optical flow [2, 6, 8, 14, 17, 21, 22, 23, 24, 26, 30, 34].

2) Stereo [18, 19, 28, 33], including dyamic stereo and binocular optical flow [9, 15]; see also [27] on mathcing.

3) Range sensing and analysis of range data [31, 32].

4) Three-dimensional object recognition and the geometry of 3D vision [4, 20, 25, 29, 35, 36].

5) Tracking, visibility, and path planning [10, 11, 12, 16; see also 1, 3, 5].

Two other reports dealt with color edge detection [13] and with software [7].

ABSTRACTS OF TECHNICAL REPORTS

1. Takashi Matsuyama and Tsai-Yun Phillips. "Extracting the Medial Axis from the Voronoi Diagram of Boundary Segments: An Alternative Method for Closed Boundary Detection." CAR-TR-2, CS-TR-1261, April 1983.

ABSTRACT: An algorithm to recover closed boundaries from disconnected boundary segments is presented. There is a close relation between the medial axis transform and the Voronoi diagram. Here we introduce a geometric labeling scheme for the Voronoi diagram of boundary segments, and recover the medial axes of closed boundaries by using the labeled Voronoi diagram. Although all examples given in this paper are pictures of straight line segments in the two-dimensional Euclidean plane, the basic idea is immediately applicable to digital pictures with curved segments.

2. Hu-Chen Xie, Kwangyoen Wohn, Larry S. Davis and Azriel Rosenfeld, "Optical Flow Field Smoothing by Local Use of Global Information." CAR-TR-3, CS-TR-1274, April 1983.

ABSTRACT: This paper describes a method for image motion enhancement which utilizes global information about the motion field, derived from the histograms of the components of the estimated motion. The method is an adaptation of the "superspike" image enhancement algorithm to motion field estimation. Experiments indicate that the method can yield more accurate and precise estimates of motion than previously proposed motion estimation algorithms.

3. Tsai-Yun Phillips and Takashi Matsuyama, "The Labeled Discrete Voronoi Diagram." CAR-TR-4, CS-TR-1278, May 1983.

ABSTRACT: Generalized Voronoi diagrams of sets of digital curves are a helpful tool in picture analysis. In this paper, an algorithm for computing labeled Voronoi diagrams for digital straight line segments is given. Special emphasis was given to the use of a labeled Euclidean distance transform. This transform is the key feature of the proposed label propagation process. The proposed parallel algorithm for computing labeled Voronoi diagrams has time complexity $O(\max\{M, N\})$ for input pictures of size $N \times M$ using a mesh-connected array processor. The proposed serial algorithm for computing labeled Voronoi diagrams has time complexity $O(MN)$.

4. Teresa M. Silberberg, Larry Davis and David Harwood, "An Iterative Hough Procedure for Three-Dimensional Object Recognition." CAR-TR-20, CS-TR-1317, August 1983.

ABSTRACT: This paper describes an iterative Hough procedure for recognizing images of three-dimensional objects. Straight line segments in the image are matched by finding the parameters of a viewing transformation of a three-dimensional model consisting of line segments. Assuming the scale of the object is known, there are three orientation and two translation parameters to be estimated. Initially a sparse, regular subset of parameters and transformations is evaluated for goodness-of-fit; then the procedure is repeated by successively subdividing the parameter space near current best estimates of peaks.

5. Takashi Matsuyama and Tsai-Yun Phillips, "Digital Realization of the Labeled Voronoi Diagram and Its Application to Closed Boundary Detection." CAR-TR-22, CS-TR-1328, October 1983.

ABSTRACT: An algorithm to compute the labeled Voronoi diagram of a set of line segments in a digital picture is presented. The algorithm for extracting the medial axis from the labeled Voronoi diagram [1] is also implemented. Experimental results have shown that both algorithms can be used to construct closed boundaries from disjoint line segments in a digital picture.

6. Allen M. Waxman and Kwangyoen Wohn, "Contour Evolution, Neighborhood Deformation and Global Image Flow: Planar Surfaces in Motion." CAR-TR-58, CS-TR-1394, April 1984.

ABSTRACT: In the kinematic analysis of time-varying imagery, where the goal is to recover object surface structure and space motion from image flow, an appropriate representation for the flow field consists of a set of *deformation parameters* which describe the rate-of-change of an image neighborhood. In this paper we develop methods for extracting these deformation parameters from *evolving contours* in an image sequence; the image contours being manifestations of surface texture of the underlying image flow; no heuristics are imposed. The deformation parameters we seek are actually linear combinations of the Taylor series coefficients (through second derivatives) of the local image flow field. Thus, a by-product of our approach is a second-order polynomial approximation to the image flow in the neighborhood of a contour. For curved surfaces this approximation is only locally valid, but for planar surfaces it is globally valid (i.e., it is exact). Our analysis reveals an "aperture problem in the large" in which insufficient contour structure leaves the set of twelve deformation parameters under-determined. We also assess the sensitivity of our method to the simulated effects of noise in the "normal flow" around contours, as well as the angular field of view subtended by contours. The sensitivity analysis is carried out in the context of planar surfaces executing general rigid body motions in space. Future

work will address the additional considerations relevant to curved surface patches.

7. Fred P. Andresen, "The Franz Lisp — C Interface." CAR-TR-68, CS-TR-1411, June 1984.

ABSTRACT: The programming languages Lisp and C have complementary powers. Lisp is very high level and C can be very low level. For this reason it can be extremely worthwhile to combine their favorable features. Although briefly mentioned in Section 8.4 of the Franz Lisp manual, the topic is not covered in detail. This document elaborates and expands considerably on that section in the manual. Several examples are given. A quick and easy section for those with limited need is also included.

8. Sarvajit S. Sinha and Allen M. Waxman, "An Image Flow Simulator." CAR-TR-71, CS-TR-1417, July 1984.

ABSTRACT: The analysis of time-varying images is currently of great interest in computer vision. There has been a deal of work recently in the study of the 2-D image flow produced due to space motion, and the recovery of the object's 3-D structure and space motion from the flow. This report details the reverse process implemented in the form of an Image Flow Simulator; from a knowledge of structure and motion, to display the 2-D image sequence and associated flow. This 3-D graphics animation package simulates motion of objects through space and also the evolution of surface contours through time. The graphics algorithms for projection, clipping, hidden surface removal, shading and animation are described in this report.

9. Allen M. Waxman and Sarvajit S. Sinha, "Dynamic Stereo: Passive Ranging to Moving Objects from Relative Image Flows." CAR-TR-74, CS-TR-1421, July 1984.

ABSTRACT: A new concept in passive ranging to moving objects is described which is based on the comparison of multiple image flows. It is well know that if a static scene is viewed by an observer undergoing a known relative translation through space, then the distance to objects in the scene can be easily obtained from the measured image velocities associated with features on the objects (i.e., motion stereo). But in general, individual objects are translating and rotating at unknown rates with respect to a moving observer whose own motion may not be accurately monitored. The net effect is a complicated image flow field in which absolute range information is lost. However, if a second image flow field is produced by a camera whose motion through space differs from that of the first camera by a known amount, the range information can be recovered by subtracting

the first image flow from the second. This "difference flow" must then be corrected for the known relative rotation between the two cameras, resulting in a divergent relative flow from a known focus of expansion. This passive ranging process may be termed *Dynamic Stereo*, the known difference in camera motions playing the role of the stereo baseline. We present the basic theory of this ranging process, along with some examples for simulated scenes. Potential applications are in autonomous vehicle navigation (with one fixed and one movable camera mounted on the vehicle), coordinated motions between two vehicles (each carrying one fixed camera) for passive ranging to moving targets, and in industrial robotics (with two cameras mounted on different parts of a robot arm) for intercepting moving workpieces.

10. Mark F. Doherty, "Computation of Minimal Isovist Sets," CAR-TR-87, CS-TR-1436, September 1984.

ABSTRACT: A minimal isovist set (MIS) of a simple polygonal region P is a smallest set of points in P whose union of isovists equals P (where the isovist of x is the set of all points visible from x). This thesis presents an algorithm to search for an MIS for an arbitrary P An MIS is shown to be equivalent to a minimal covering of P with star-shaped polygons. A (non-complete) algorithm to find a minimal covering is proposed which uses the vertices of the kernels of the star-shaped polygons. The complexity of finding an MIS is reduced to a worst-case consideration of no more than n^4 points in P. A comparison of the proposed algorithm with two previously published algorithms is made. Extension of this method to exterior views and interior holes is discussed, and areas for future research are mentioned.

11. Nader Kazor, "Target Tracking Based Scene Analysis," CAR-TR-88, CS-TR-1437, August 1984.

ABSTRACT: Target Tracking and 3-D Scene Analysis are two research areas in Computer Vision which in the past have been considered separately. However, there are many advantages in combining the two problems. One such advantage would be the ability to analyze and build a model of a stationary scene/environment through which dynamic objects move. This is possible through tracking the moving objects and detecting instances of occlusion. This work is based on such an idea and is concerned with the design of an Intelligent Target Tracking System (ITTS) which combines the above two problems into one. In this paper we present an experimental ITTS which generates a perspective and ground map of a stationary environment.

12. Frederick P. Andresen and Larry S. Davis, "Visual Position Determination for Autonomous Vehicle Navigation," CAR-TR-100, CS-TR-1458, November 1984.

ABSTRACT: This report describes a system by which an autonomous land vehicle might improve its estimate of its current position. This system selects visible landmarks from a database of knowledge about its environment and controls a camera's direction and focal length to obtain images of these landmarks. The landmarks are then located in the images using a modified version of the generalized Hough transform and their locations are used to triangulate to obtain the new estimate of vehicle position and position uncertainty.

13. Matti Pietikainen and David Harwood, "Edge Information in Color Images Based on Histograms of Differences," CAR-TR-112, CS-TR-1479, March 1985.

ABSTRACT: A new measure of edge information for color images based on cumulative histograms of absolute color differences is proposed. A multispectral version of the Symmetric Nearest Neighbor filter for edge-preserving smoothing and methods for image segmentation and edge detection are developed based on this measure. Experimental results show that the performance of the new algorithms is very good.

14. Muralidhara Subbarao and Allen Waxman, "On the Uniqueness of Image Flow Solutions for Planar Surfaces in Motion," CAR-TR-114, CS-TR-1485, April 1985.

ABSTRACT: Two important results relating to the uniqueness of image flow solutions for planar surfaces in motion are presented here. These results relate to the formulation of the image flow problem by Waxman and Ullman [1], which is based on a kinematic analysis of the image flow field. The first result concerns resolving the duality of interpretations that are generally associated with the instantaneous image flow of an evolving image sequence. It is shown that the interpretation for orientation and motion of planar surfaces is unique when either two successive image flows of one planar surface patch are given or one image flow of two planar patches moving as a rigid body is given. We have proved this by deriving explicit expressions for the evolving solution of an image flow sequence with time. These expressions can be used to resolve this ambiguity of interpretation in practical problems. The second result is the proof of uniqueness for the velocity of approach which satisfies the image flow equations for planar surfaces derived in [1]. In addition, it is shown that this velocity can be computed as the middle root of a cubic equation. These two results together suggest a new method for solving the image flow problem for planar surfaces in motion.

15. Allen M. Waxman and James H. Duncan. "Binocular Image Flows: Steps Toward Stereo - Motion Fusion." CAR-TR-119, CS-TR-1494, May 1985.

ABSTRACT: The analyses of visual data by stereo and motion modules have typically been treated as separate, parallel processes which both feed a common viewer-centered 2.5-D sketch of the scene. When acting separately, stereo and motion analyses are subject to certain inherent difficulties; stereo must resolve a combinatorial correspondence problem and is further complicated by the presence of occluding boundaries, motion analysis involves the solution of nonlinear equations and yields a 3-D interpretation specified up to an undetermined scale factor. A new module is described here which unifies stereo and motion analysis in a manner in which each helps to overcome the other's shortcomings. One important result is a *correlation between relative image flow (i.e., binocular difference flow) and stereo disparity*; it points to the importance of the ratio δ/δ, rate of change of disparity δ to disparity δ, and its possible role in establishing stereo correspondence. Our formulation may reflect the human perception channel probed by Regan and Beverley (1979).

16. Subbarao Kambhampati and Larry S. Davis, "Multiresolution Path Planning for Mobile Robots." CAR-TR-127, CS-TR-1507, May 1985.

ABSTRACT: The problem of automatic collision-free path planning is central to mobile robot applications. In this report, we present an approach to automatic path planning based on a quadtree representation. We introduce hierarchical path searching methods, which make use of this multiresolution representation, to speed up the path planning process considerably. Finally, we discuss the applicability of this approach to mobile robot path planning.

17. Kwangyoen Wohn and Allen M. Waxman, "Contour Evolution, Neighborhood Deformation and Local Image Flow: Curved Surfaces in Motion." CAR-TR-134, CS-TR-1531, July 1985.

ABSTRACT: In our earlier paper (Waxman and Wohn 1984), we developed an algorithm, the Velocity Functional Method, to recover an image flow field from time-varying contours. The method follows directly from the analytic structure of the underlying image flow; no heuristics are imposed. Local image flow is modeled as a second-order Taylor series. The method computes twelve series coefficients from the normal component of image flow measured along contours. For planar surfaces in motion, the method yields the exact flow. We have demonstrated the robustness of our algorithm by carrying out the sensitivity analysis in the context of planar surfaces executing general rigid body motions in space.

This paper explores the additional aspects of the theory for curved surfaces, where the second-order flow approximation is only locally valid. We derive the dependence of the truncation error on surface curvature and field of view. We also investigate the sensitivity of solutions to noise in the normal flow. The combined algorithms of 2-D flow estimation and 3-D structure and motion recovery are not as stable to input noise and surface structure as is the case for planar surfaces. The use of multiple frames to overcome the effects of noise is currently under study (cf. Waxman and Wohn 1985).

18. Roger D. Eastman and Allen M. Waxman, "Using Disparity Functionals for Stereo Correspondence and Surface Reconstruction." CAR-TR-145, CS-TR-1547, October 1985.

ABSTRACT: In this paper, we investigate stereo matching constraints that derive from an analytic model of surface depth. Analyticity is the mathematical tool by which we model smoothness of object surfaces, and therefore the disparity field, as piecewise analytic functions of visual direction. Our model of *analytic coherence* mathematically formulates the principle of *coherence* stated by Prazdny [23], and can describe transparent as well as opaque surfaces. In using this property, we follow the work in stereo of Koenderink and van Doorn [12] and our own work on motion (Waxman and Ullman [31], Waxman [29], Waxman and Wohn [32, 34]). We formulate stereo as a single stage process in which potential feature point or contour matches interact to provide support for local estimates of a polynomial model of disparity (the *disparity functional*), not just estimates of disparity at isolated points. This refines the notion of local support defined by Marr and Poggio [17]. We present an algorithm that integrates the disparity functional with multiresolution matching of zero-crossings to derive depth to surface patches. The analyticity of the disparity field is thereby exploited early in the matching process, and yields surface reconstruction as a direct byproduct of correspondence.

19. Matti Pietikäinen and David Harwood, "Multiple-Camera Contour Stereo." CAR-TR-151, CS-TR-1559, September 1985.

ABSTRACT: A three-camera approach for computational stereo is presented, which greatly simplifies the search problem among candidate matches and allows matching of horizontal edges. Only a simple camera geometry is considered, in which the images are rectified in the same plane. The horizontal and vertical images are equidistant from and aligned parallel to the base image. The primitive objects of the approach are labeled edge segments, i.e., 8-connected chains of edge points with their local image properties. The matching algorithm scans through the edge segments in the base image and searches for corresponding triples of points in the three images. Local properties of points are used to classify matches. A preliminary evaluation of matches is based on goodness of match

criteria. A simple postprocessing method based on contour connectivity is used to eliminate false matches. The method performs well in experiments. The basic matching algorithm generates only a few false matches and most of these can be easily eliminated.

20. Ambjörn Naeve and Jan-Olof Eklundh, "On Projective Geometry and the Recovery of 3-D Structure," CAR-TR-154, CS-TR-1565, October 1985.

ABSTRACT: Geometric properties are of key importance in the recovery of scene structure from images. It is argued that the proper formulations of the determination of scene geometry are obtained when projective geometry is used. A framework of projective geometry for computer vision is presented in brief and its applicability is demonstrated in a simple example. A computational approach to finding the necessary primitives is reviewed.

21. Ken-ichi Kanatani, "Analysis of Structure and Motion from Optical Flow, Part I: Orthographic Projection," CAR-TR-160, CS-TR-1576, October 1984, Revised June 1985.

ABSTRACT: The 3D structure and motion of an object is determined from its optical flow under orthographic projection. First, the image domain is divided into planar or almost planar regions by checking the flow. For each region, parameters of the flow are determined. Transformation rules under coordinate changes and hydrodynamic analogies are also discussed. The 3D structure and motion are determined in explicit forms in terms of irreducible parameters deduced from group representation theory. The solution is not unique, containing an indeterminate scale factor and comprising true and spurious solutions. Their geometrical interpretations are also studied. The spurious solution disappears if two or more regions of the object are observed.

22. Ken-ichi Kanatani, "Analysis of Structure and Motion from Optical Flow, Part II: Central Projection," CAR-TR-161, CS-TR-1577, January 1985, Revised June 1985.

ABSTRACT: In this Part 2, the 3D structure and motion of an object is determined from its optical flow in central projection. As in Part 1, the image domain is divided into planar or almost planar regions by checking the flow. For each region, parameters of the flow are determined. In our flow-based approach, the 3D structure and motion are computed from the irreducible parameters, which are complex numbers in general, deduced from group representation theory. The transition from central projection via "pseudo-orthographic projection" to orthographic projection is also discussed. The solution is not unique. Besides the absolute depth being indeterminate, there arise two solutions, the true one and a

spurious one. However, the spurious solution disappears if two regions of the object are observed. The adjacency condition of two planar regions is also studied in terms of complex variables. The relation to the correspondence-based approach is shown, too.

23. Ken-ichi Kanatani, "Transformation of Optical Flow by Camera Rotation." CAR-TR-163, CS-TR-1580, November 1985.

ABSTRACT: The effect of camera rotation on the description of optical flow is analyzed. The transformation law of the parameters is explicitly given by considering infinitesimal generators and irreducible reduction of the induced representation of the 3D rotation group. The parameter space is decomposed into invariant subspaces, and the optical flow is accordingly decomposed into two parts, from which an invariant basis is deduced. A procedure is presented to test the equivalence of two optical flows and to reconstruct the necessary amount of camera rotation. The relationship with the analytical expressions for 3D recovery is also discussed.

24. Ken-ichi Kanatani, "Structure from Motion without Correspondence: General Principle." CAR-TR-164, CS-TR-1581, November 1985.

ABSTRACT: A general principle is given for detecting 3D structure and motion from an image sequence without using point-to-point correspondence. The procedure consists of two stages: (i) determination of the *flow parameters*, which completely characterize the motion of the planar part of the object, and (ii) computation of 3D recovery from these flow parameters. The first stage is done by measuring *features* of the image sequence. The second stage is analytically expressed in terms of invariants with respect to coordinate changes. Typical features and relations to stepwise tracing are also discussed.

25. Ken-ichi Kanatani, "The Constraints on Images of Rectangular Polyhedra." CAR-TR-165, CS-TR-1582, November 1985.

ABSTRACT: This paper discusses how polyhedron interpretation techniques are simplified if the objects are rectangular trihedral polyhedra. This restriction enables one to compute the spatial orientation of a given corner and its motion from its image. The solution is expressed in terms of polar coordinates, Eulerian angles and quaternions. Then, based on the fact that the transformations mapping eight possible configurations of the rectangular corner to each other form a group isomorphic to $Z_2 \times Z_2 \times Z_2$, the corner configurations, their transformations, spatial orientations and states of face adjacency are expressed by triplets of binary bits, and the conditions constraining relationships among them are described in algebraic equations in terms of those triplets. Finally, the visibility

con ons are formulated, and an algorithm of shape interpretation and hidden line detection from "local" information is presented. Some examples are given to compare our scheme with existing ones. The possible non-uniqueness of the interpretation and the effect of projective distortion are also discussed.

26. Muralidhara Subbarao, "Interpretation of Image Motion Fields: A Spatio-Temporal Approach." CAR-TR-167, CS-TR-1589, December 1985.

ABSTRACT: In this paper we describe a new formulation of the image motion interpretation problem. The formulation addresses the general problem of recovering the 3D local surface structure, motion and deformation of an opaque object. It is based on the assumption of local analyticity of 3D surface structure, motion, deformation and, consequently, the corresponding 2D image motion in the space-time domain. In this approach both spatial and temporal information are used in a uniform way. The formulation is very general in the sense that as long as the analyticity assumption is valid, the space and time dependence of surface structure and motion can be related to the image motion parameters. We illustrate our approach by formulating and solving the image motion interpretation problem for some simple cases including non-rigid and non-uniform motions. However, it can be easily extended to deal with more complicated cases.

For rigid and uniform motions we have solved the problem for three important cases. The first two relate to the case where the image motion is observed in a fixed image neighborhood and the other case is where the camera tracks a fixed point on the object in motion and the tracking motion of the camera is known. In all these three cases we have solved for the local orientation and rigid motion of the surface patch around the line of sight using only the first-order spatial and temporal derivatives of the image velocity field. In comparison, all the existing methods based on image motion fields use up to second-order spatial derivatives of the image velocity field which are relatively sensitive to noise.

27. Eliahu Wasserstrom, "Subpixel Registration." CAR-TR-173, CS-TR-1601, January 1986.

ABSTRACT: A method of subpixel image registration is proposed that employs a model of the correlation surface in the vicinity of the registration point.

28. Fang-Jyh Lin Liu, Roger Eastman and Larry S. Davis. "Experiments in Stereo Matching using Multiresolution Local Support." CAR-TR-183, CS-TR-1617, January 1986.

ABSTRACT: This paper describes a set of computational algorithms for stereo matching based on multiresolution local support. The algorithms combine the feature-point based coarse-to-fine matching of Marr-Poggio-Grimson, the local support measures of Pollard-Mayhew-Frisby and Prazdny, and other disambiguation techniques. The matching primitives are zero-crossing points. Matching compatibility is based on the sign of the contrast and the gradient direction at the Laplacian zero-crossing point. These algorithms use coarse resolution disparity to constrain the disparity search window in the fine resolution matching process, which speed up the search and greatly improve the accuracy of matching. The consistency measure includes Gaussian local support or disparity gradient threshold local support in combination with symmetric or iterative disambiguation techniques. This paper includes experiments performed on a variety of stereo images containing synthetic, laboratory and aerial scenes.

29. Ken-ichi Kanatani and Tsai-Chia Chou, "Shape from Texture: General Principle." CAR-TR-184, CS-TR-1618, February 1986.

ABSTRACT: The 3D shape of a textured surface is recovered from its projected image on the assumption that the texture is homogeneously distributed. First, the homogeneity of a discrete texture consisting of dots and line segments is defined in terms of the theory of distributions. Next, distortion of the observed texture density due to perspective projection is described in terms of the first fundamental form, which is expressed with respect to the image coordinate system. Based on this result, the basic equations to determine the surface shape are derived for both planar and curved surfaces, and numerical schemes are proposed to solve them. Necessary data are obtained in the form of summation or integration of functions over the texture elements on the image plane. Ambiguity in the interpretation of curved surfaces is also analyzed. Finally, numerical examples for synthetic data are presented, and our method is compared with other existing methods. It is shown that all other methods can be explained in terms of our formulation.

30. Allen M. Waxman, Behrooz Kamgar-Parsi and Muralidhara Subbarao, "Closed-Form Solutions to Image Flow Equations for 3-D Structure and Motion." CAR-TR-190, CS-TR-1633, February 1986.

ABSTRACT: A major source of three-dimensional (3-D) information about objects in the world is available to the observer in the form of time-varying imagery. Relative motion between textured objects and observer generates a time-varying optic array at the image, from which image motion of contours, edge fragments and feature points can be extracted. These dynamic features

serve to sample the underlying "image flow" field. New, closed-form solutions are given for the structure and motion of planar and curved surface patches from monocular image flow and its derivatives through second order. Both planar and curved surface solutions require at most, the solution of a cubic equation. The analytic solution for curved surface patches combines the transformation of Longuet-Higgins and Prazdny (1980) with the planar surface solution of Subbarao and Waxman (1985). New insights regarding uniqueness of solutions also emerge. Thus, the "structure-motion coincidence" of Waxman and Ullman (1983) is interpreted as the "duality of tangent plane solutions." The multiplicity of transformation angles (up to three) is related to the sign of the Gaussian curvature of the surface patch. Ovoid patches (i.e., bowls) are shown to possess a unique transform angle, though they are subject to the local structure-motion coincidence. Thus, ovoid patches almost always yield a unique 3-D interpretation. In general, ambiguous solutions can be resolved by requiring continuity of the solution over time.

31. Jacqueline Le Moigne and Allen M. Waxman, "Structured Light Patterns for Robot Mobility," CAR-TR-191, CS-TR-1634, February 1986.

ABSTRACT: In order to assess the feasibility of using a structured-light range sensor for mobile outdoor and indoor robots, we discuss a number of operational considerations and image processing tools relevant to this task domain. In particular, we address the issues of operating in ambient lighting, smoothing of range texture, grid pattern selection, albedo normalization, grid extraction and coarse registration of image to projected grid. Once a range map of the immediate environment is obtained, short range path planning can be attempted.

32. Uma Kant Sharma and Larry S. Davis, "Road Following by an Autonomous Vehicle Using Range Data," CAR-TR-194, CS-TR-1639, March 1986.

ABSTRACT: This paper describes a road following system for an Autonomous Land Vehicle. Range data is used as the sensor input. The system is divided into two parts: low-level data driven analysis followed by high-level model-directed search. The sequence of steps performed, in order to detect 3-D road boundaries, is as follows: Range data is first converted from spherical into Cartesian coordinates. A quadric (or planar) surface is then fitted to the neighborhood of each range pixel, using a least square fit method. Based on this fit, minimum and maximum principal surface curvatures are computed at each point to detect edges. Next, using Hough transform techniques 3-D local line segments are extracted. Finally, model directed reasoning is applied to detect the road boundaries.

33. Behrooz Kamgar-Parsi. "Practical Computation of Pan and Tilt Angles." CAR-TR-195, CS-TR-1640, March 1986.

ABSTRACT: The sensitivity of the 3-D recovery from a stereo pair of images of object points in space to the errors in the pan and tilt angles is studied. It is shown that precise knowledge of the relative pan angle of the two cameras with respect to each other (and to a lesser degree the relative tilt angle) is crucial to the accurate 3-D recovery of object points in space, whereas accurate knowledge of the pan and tilt angles relative to the scene, i.e. the "world" angles, is of less significance. This indicates that the most important task would be the computation of the relative pan and tilt angles. Theoretically, it is well known that using corresponding left and right image positions, one can calculate the orientation of the two cameras. Limited resolution capabilities of existing cameras, however, makes this task a difficult one. Practical difficulties in computation of camera orientations are discussed. It is shown that while computation of the relative tilt angle is fairly easy, computation of the relative pan and in particular the world pan angles are difficult. Indeed for many image pairs it may not be possible to compute the world pan angle with any degree of reliability. However, it is shown that often it is possible to bypass the computation of the world pan angle and to compute the relative pan and tilt angles directly. This is despite the fact that in the analytic formulation of the problem the three angles are coupled. The stereo model studied here is assumed to have a fixed baseline and small relative pan and tilt angles. A possible application of such a stereo model is the visual system of an autonomous vehicle whose task is road following.

34. Muralidhara Subbarao, "Interpretation of Image Motion Fields: Rigid Curved Surfaces in Motion." CAR-TR-199, CS-TR-1654, April 1986.

ABSTRACT: This paper is concerned with recovering the three-dimensional shape and motion of a rigid surface from its image motion field on a camera's image plane. A partial solution to this problem was proposed by Longuet-Higgins and Prazdny [1], and recently a more complete solution has been obtained by Waxman, Kamgar-Parsi and Subbarao [2]. Here we reconsider this problem in the context of our recent work [3] where a general formulation and solution procedure is proposed for the interpretation of image motion fields. Using this new approach, closed-form solutions are derived for the motion, orientation and curvatures of a rigid surface. In comparison with the previous approaches [1,2] this approach does not involve rotating the image coordinate system in order to solve for the unknowns. The solution is obtained directly in the original coordinate system, thus saving some computation. More importantly we state and prove some fundamental theoretical results concerning the existence of multiple interpretations for an instantaneous image motion field resulting from a rigid body motion. *Conditions for the occurrence of up to four (four being the maximum possible) solutions are stated and proved.* Numerical examples are given for some interesting cases where multiple solutions exist. The results are presented in a sequential order which suggests a straightforward implementation of the solution method.

This work, along with our previous work [3,12] suggests a unified computational approach for the interpretation of image motion fields in a variety of situations (e.g.: planar/curved surfaces using spatial and/or temporal image flow parameters, rigid/non-rigid motion, etc.)

35. Ken-ichi Kanatani, "Constraints on Length and Angle," CAR-TR-200, CS-TR-1655, April 1986.

ABSTRACT: Given a perspective projection of line segments on the image plane, the constraints on their 3D positions and orientations are derived when their true length or the true angles they make are known. The line segments under consideration are first mapped to the center of the image plane as if the camera were rotated to aim at them. Then, the constraints are given by the geometry of perspective transformation, and the relations obtained are transformed back to the original configuration in the scene. An application is given to the interpretation of rectangular corners of polyhedra.

36. Ken-ichi Kanatani, "Camera Rotation Invariance of Image Characteristics," CAR-TR-202, CS-TR-1663, May 1986.

ABSTRACT: The image transformation due to camera rotation relative to a stationary scene is analyzed, and the associated transformation rules of "features" given by weighted averaging of the image are derived by considering infinitesimal generators on the basis of group representation theory. Three dimensional vectors and tensors are reduced to two dimensional invariants on the image plane from the viewpoint of projective geometry. Three dimensional invariants and camera rotation reconstruction are also discussed. The result is applied to the shape recognition problem when camera rotation is involved.

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Research on "Autonomous Vehicle Navigation", carried out during the period 1983-5, has dealt primarily with the following areas:

a) Time-varying image analysis
b) Stereo and range sensing
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